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ANISOTROPY EFFECTS IN A DEEP EXCAVATION IN STIFF CLAY

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Abstract. This paper tackles the issues related to the excavation of a horizontal gallery carried out in Boom clay, a tertiary clay that hosts the Underground Laboratory of the Belgium Nuclear Agency (SCK-CEN). The gallery is 85 m long, 5 m wide and connects one of the laboratory access shafts to a horizontal drift drilled from the second access shaft. Displacement and pore water pressure sensors installed from both gallery ends allowed for a detailed monitoring of the hydro-mechanical response of the clay rock before, during and after gallery excavation. A striking feature of the response concerns the strong changes measured in pore water pressure at distances as large as 60m from the excavation front. To explore and discriminate the mechanisms controlling such pore pressure changes, 2D axisymmetric Finite Element hydro-mechanical calculations have been carried out. An elastoplastic constitutive law based on Mohr-Coulomb criterion has been considered for the material. Several types of analyses have been performed: a) material and stress state are isotropic; b) material is isotropic but stress state is orthotropic and, c) material and stress state are orthotropic. Results allow for explaining the field measurements and identifying the key variables that control the clay response around the drift.

1 INTRODUCTION

Burial of nuclear waste at high depths (several hundreds of meters) is one of the solutions envisaged for a safe storage of radioactive elements along their whole life. The construction of such deep repositories requires the realization of many excavations: access shafts, access galleries, operation galleries and alveoli to store waste containers. In soft argillaceous formations, the high stress release occasioned by excavation works is the cause for the development of significant hydro-mechanical perturbed zones, whose size, continuity and characteristics are of highest importance for the safety of the whole storage.

In Underground Research Laboratories constructed in argillaceous rocks, there is therefore a strong effort devoted to the assessment of the impact of excavations on the surrounding displacement and pore pressure fields. All observations indicate that underground excavations in stiff and low permeable materials causes a rearrangement of stress that traduces into pore pressure changes. Explanation to this effect has to be looked for in the undrained conditions that prevail in such material during short term excavation, in the anisotropy of the stress state and in the anisotropy and non-linearity of material behaviour. In this paper, Finite Element modelling of the CLIPEX experiment, performed in the HADES underground research laboratory at Mol (Belgium) [1] is used to provide keys about some factors controlling pore pressure changes during excavation in Boom clay formation.

2 THE CLIPEX EXPERIMENT

Figure 1 shows a general picture of HADES URL. Construction of the URL starts in 1980 by the excavation of the first access shaft and the realization of a gallery at 224 m to host several experimental works during the years 1983-1984. In 1987, a second gallery (Test drift) has been excavated next to his zone. Ten years after, excavation of the second shaft is started. Works have been completed by the drilling of the connecting gallery in 2001-2002.

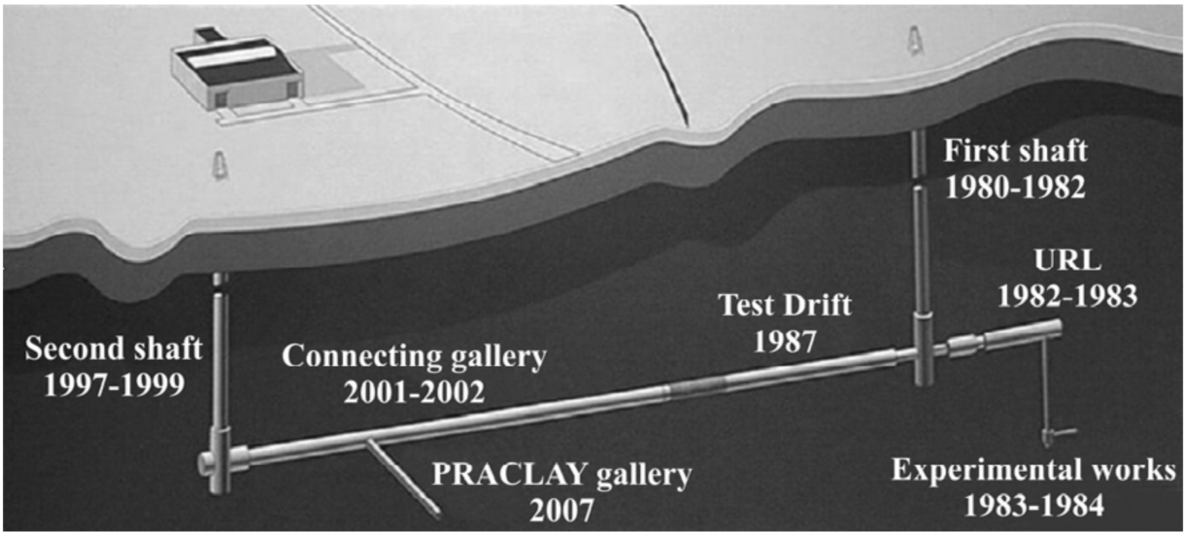

Figure 1: Location of the connecting gallery at HADES Underground Research Laboratory

A tunneling machine equipped with a road header sheltered by a tunneling shield has been used for the excavation of the connecting gallery. The tunneling machine was mounted in a chamber close to the second shaft and advanced at a rate above 2 m/day to connect finally to the Test Drift.

The gallery is 85 m long and 5 m wide. Concrete lining was installed behind the shield as excavation progressed, using the wedge-block technique to limit to the minimum the convergence of the clay. Excavation works were completed in 37 days.

Figure 2 show the detail of the instrumentation around the connecting gallery. Eight thirty meter long boreholes (A1, A2, B1, B2, C1, C2, D1 and D2) were drilled behind the front of the Test drift. A1 host a six anchors extensometer, B1 and C1 two ten-segments inclinometers and D1 one deflectometer composed by eleven segments. Borehole A2 to D2 were equipped with piezometers (six filters for A2, B2 and D2 and eight filters for C2). A1 and A2 are oriented along the centerline of the gallery to be excavated. B1, B2, C1 and C2 are inclined in the vertical plane passing through gallery centerline while D1 and D2 are inclined in the horizontal plane. In addition, two horizontal boreholes (E1 and E2) were drilled from the second access shaft, nearby the beginning of the connecting gallery. E1 is five meter long and has been instrumented with displacement measurements. E2 is 6.5 meters long and were equipped with pore pressure sensors. Instrumentation is completed by strain gauges embedded in lining panels. Convergences during excavation were also measured.

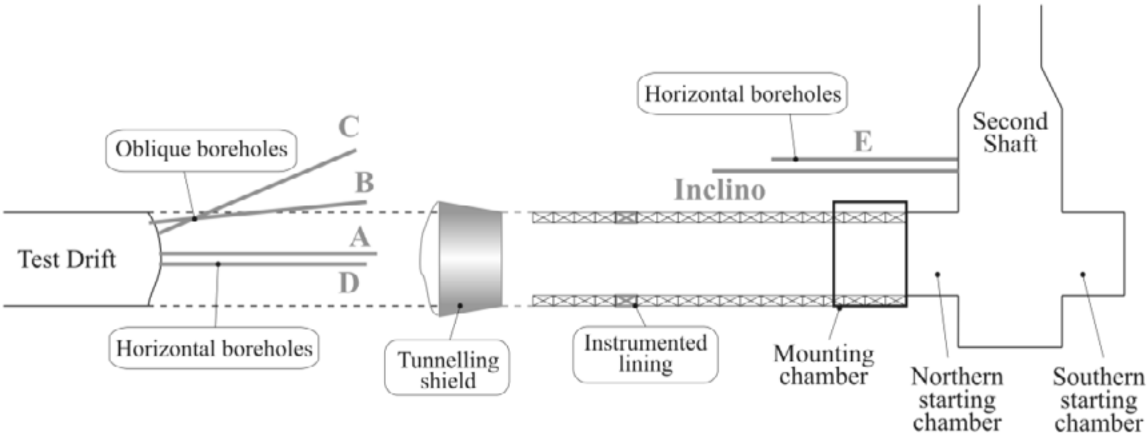

Figure 2: Layout of instrumentation around the connecting gallery

3 FEATURES OF THE MODEL

3.1 Field and constitutive equations

The solution of the coupled hydro-mechanical problem requires the simultaneous solution of the mass balance of water and stress equilibrium. In absence of water vapour (saturated problem), the water mass balance reduces to

$$\frac{\partial}{\partial t}(\rho_l \phi) + \nabla \cdot (\mathbf{j}_l) = f_l \tag{1}$$

where ϕ is the porosity, ρ_l the density of the liquid phase, $\mathbf{j}_l$, the mass flux of water and f_l an eventual source/sink term of liquid. The stress equilibrium reads:

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = \mathbf{0} \tag{2}$$

where $\boldsymbol{\sigma}$ is the stress tensor and $\mathbf{b}$ body forces.
Field equations are completed by Darcy law, that relates the Darcy flux to the gradient of water head, the state equation for water density and the mechanical law of the material.
In this work, an elastoplastic law based on linear elasticity and Mohr Coulomb yield criterion is used to represent the behaviour of Boom clay. The flow rule is considered non associated and governed by the dilation angle of the material. The elastic law can be either isotropic or orthotropic.

3.2 Material properties

Boom clay is a formation of the Rupelian Period (Tertiary age) period. It is a stiff silty clay of marine origin characterized by intercalations of layers of tens centimetres thick with different clay, silt, carbonate and organic matter contents, reflecting cyclical deposition periods. At HADES site, the formation has a thickness of 100 m and its roof culminates at a depth of 190 m. At the depth of CLIPEX experiment, the plasticity index is equal to 50%, the

porosity to 0.39 and the uniaxial compressive strength ranges between 1 and 2 MPa [2]. Pore pressure and vertical stress are equal to 2.2 and 4.5 MPa, respectively.
Several studies on natural Boom clay have been conducted in the laboratory during the last decades [3-7]. Oedometer test results presented by [3] indicate that the behaviour of the material is consistent with that of a structured clay with apparent preconsolidation caused by creep and diagenesis. The preconsolidation pressure is close to 6 MPa and the OCR to 2.4. Bernier et al. [1] pointed out the highly nonlinear response of the material. In light of this and with the objective of using simple linear elastic-plastic model, they propose to use a drained tangent Young modulus E' = 300 MPa, which provides a reasonable value of the deviatoric strain at failure. From resonant column measurements, Lima [7] suggests values between 700 and 900 MPa for the small strain Young modulus and a ratio between the horizontal and vertical component equal to 1.2. Lower values (250 and 500 MPa) were however provided by the back-analysis of a thick hollow cylinder test. As far as concerns failure parameters, Bernier et al. [1] propose to use a Mohr Coulomb type of failure locus with value of friction angle and cohesion equal to 18º and 300 kPa for stress level close to the in situ value. Dilation angle is between 0 and 10º. Finally, Lima [7] backanalysed the pore pressure evolution measured in the laboratory during a heating experiment. She found a value equal to 7.4 10-12 m/s.

Field measurements are also available for some engineering properties. Seismic measurements realized in the vicinity of the 2nd shaft give values between 1800 and 1900 m/s for the P-wave velocity. These values allow bracketing the Young modulus between 700 MPa and 1600 MPa (depending of the value of Poisson's ratio – considered between 0.125 and 0.3). Pulse test performed in two boreholes nearby the Praclay gallery gives in situ values equal, respectively, to 4 and 6 10-12 m/s for the horizontal and vertical components of the saturated permeability.
A number of analyses have been performed in which different types of anisotropy (permeability, stiffness and stress state) have been performed. The results are presented and discussed in the next section.

4 RESULTS AND DISCUSSION

Figure 3 shows a comparison between the pore overpressure due to excavation, computed by the full anisotropic model (anisotropy in permeability, stiffness and stress state) and the isotropic model for one sensor located in borehole A. It evidences shows capability of the anisotropic model to capture the peak in pore pressure as the front approaches the sensors. This is due to the loading originated by the redistribution farther ahead the front of the lateral stress released by the excavation. When the front goes closer to the sensor (less than 6 m), a sudden decrease in pore pressure is observed caused by axial unloading. The effect on pore pressure of the two last steps of excavation before it reaches the sensor can be clearly observed in the Figure. In contrast, the isotropic model captures only the pore pressure reduction by axial unloading but not the previous peak by lateral loading.

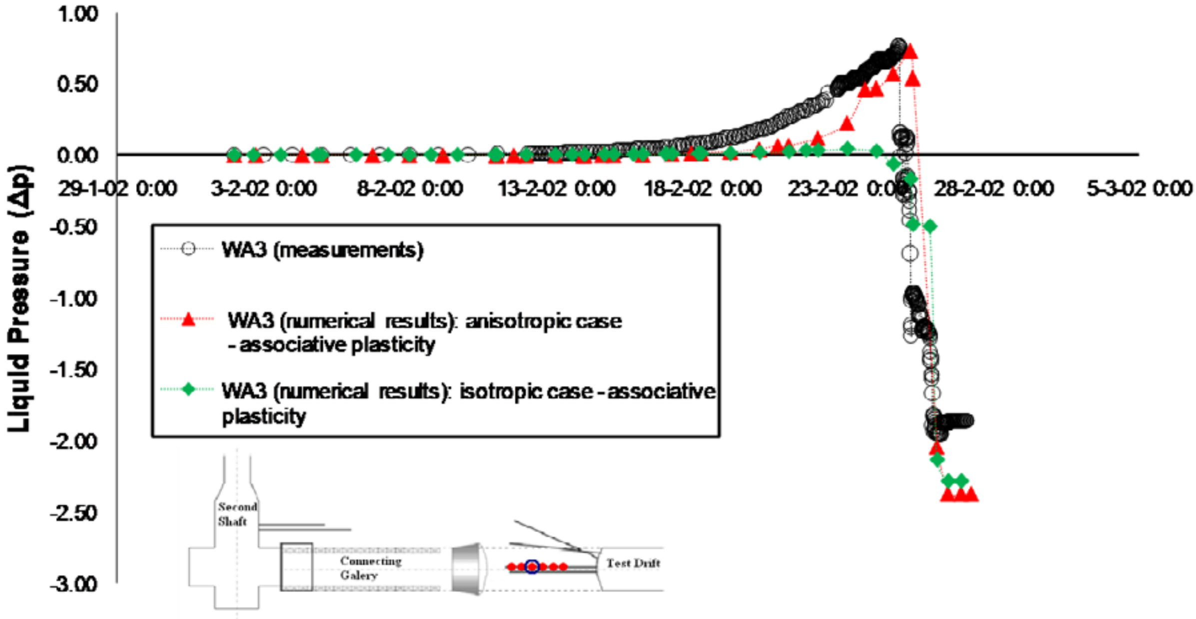

Figure 3: Evolution of pore pressures measures in sensor A3. Observed and computed values. Pore pressures have been calculated using an isotropic and a fully anisotropic (anisotropy in permeability, stiffness and stress state) model

Analyses were performed to identify whether anisotropy in permeability, stress state or moduli control mainly the pore pressure field. As a representative example, comparison between computed pore pressures and measurements at sensor A4 is reported in Figure 4 for three models: the full anisotropic model (Figure 4), the model considering anisotropy only in elastic moduli (Figure 5) and the model considering anisotropy in all variables (permeability, stress state) except for elastic moduli (Figure 6). The figure indicates clearly that the peak in pore pressure ahead the front is controlled almost exclusively by the anisotropy in moduli.

5 CONCLUDING REMARKS

Underground excavations in stiff, low permeability and saturated clayey materials exhibit strong variations of pore pressure a long distances from the excavation because of the stress rearrangement around the cavities. While the underlying mechanism may be qualitatively understood as the undrained response of anisotropic geological formations, the quantitative reproduction of the magnitude and spatial extension of pore pressure variations is still a challenging issue for numerical modelling. In this paper, experimental results obtained in a full scale Mine-by Test experiment performed at high depths in Boom clay formation are used to analyse the possible effects of different factors of anisotropy (anisotropy in stress state, permeability and stiffness) on the hydraulic response. It appears that, in this case, the anisotropy in stiffness is the main controlling factors of pore pressure variations.

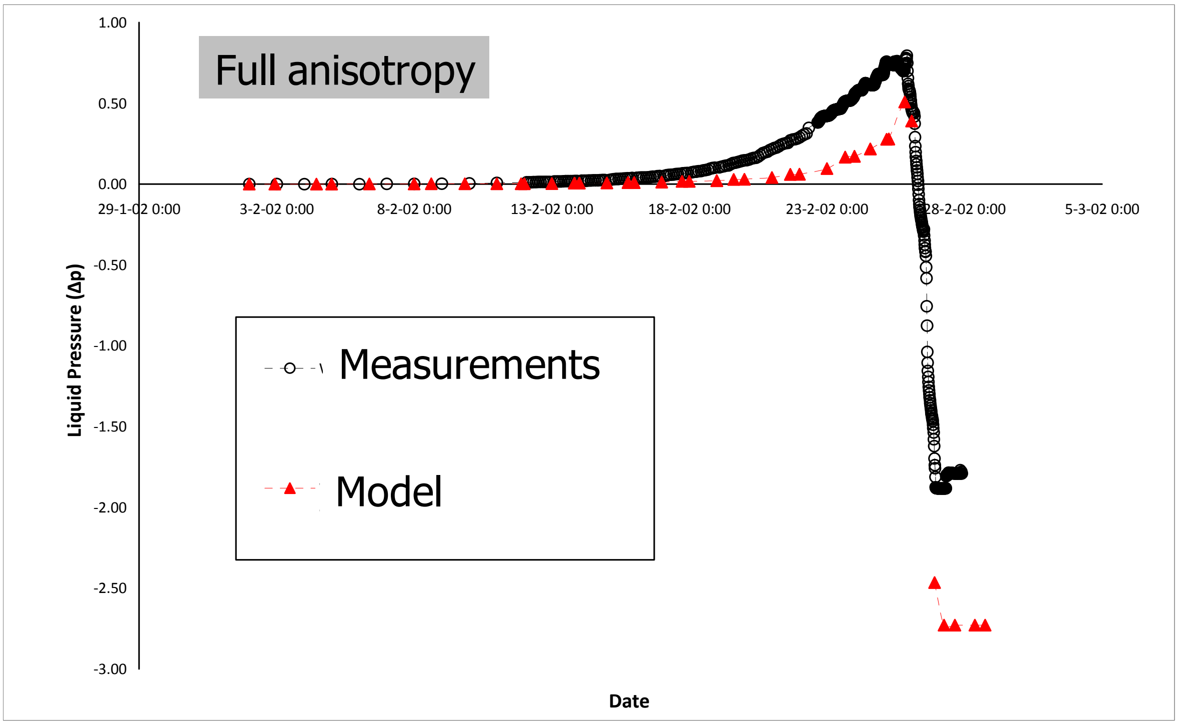

Figure 4: Evolution of pore pressures measures in sensor A4. Observed and computed values. Pore pressures have been calculated using the fully anisotropic (anisotropy in permeability, stiffness and stress state) model

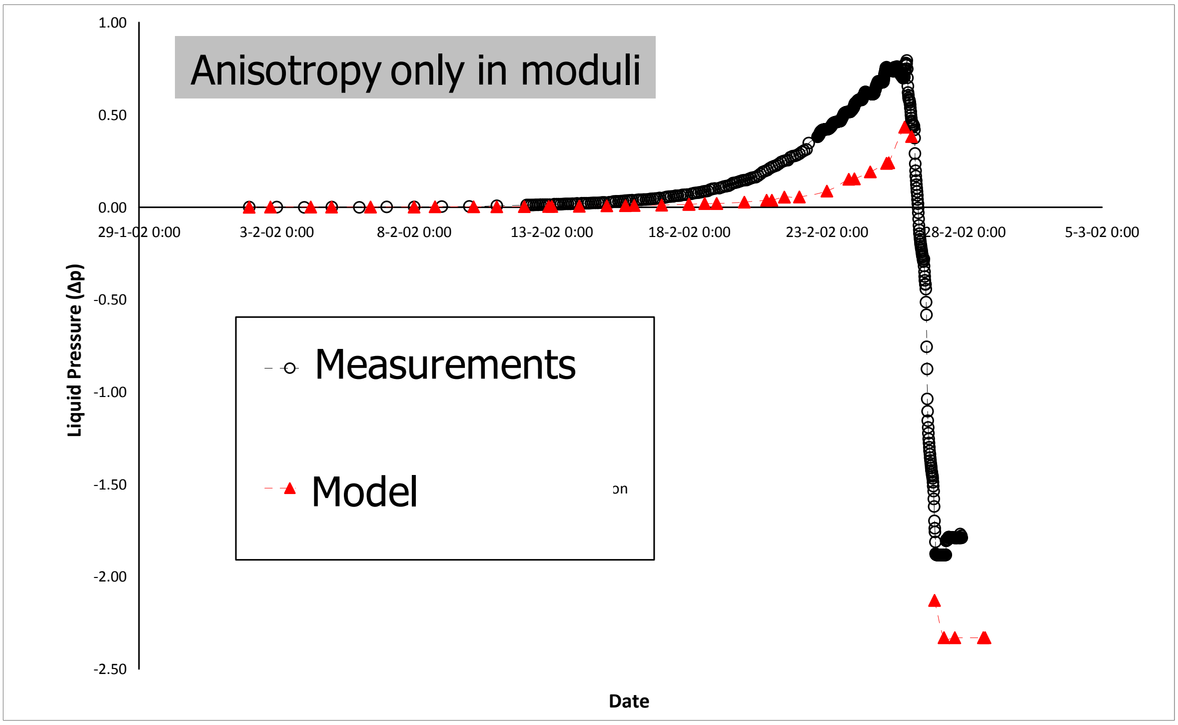

Figure 5: Evolution of pore pressures measures in sensor A4. Observed and computed values. Pore pressures have been calculated considering the anisotropy of stiffness only

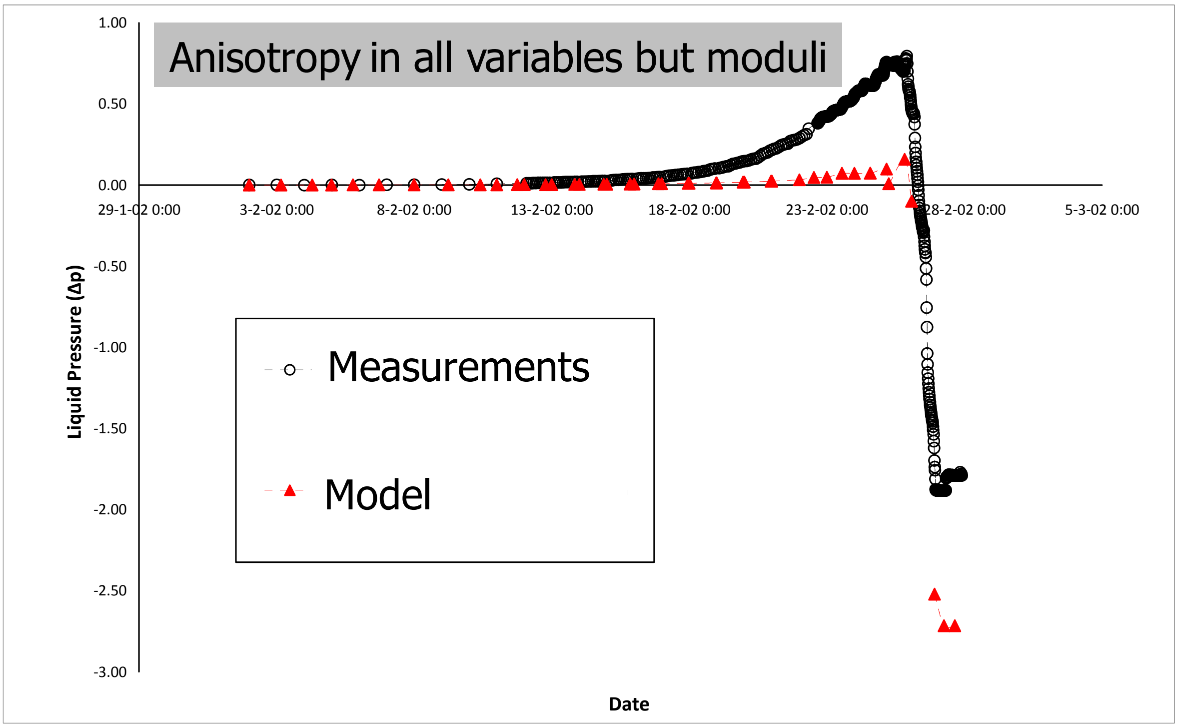

Figure 6: Evolution of pore pressures measures in sensor A4. Observed and computed values. Pore pressures have been calculated considering anisotropy of permeability and stress state

ACKNOWLEDGEMENTS

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REFERENCES

[1] Bernier, F., Li, X.L. and Bastiaens, W. Twenty-five years geotechnical observations and testing in the Tertiary Boom Clay formation, *Géotechnique* (2007) **57**: 229-237.
[2] Bastiaens, W., Bernier, F. and Li, X. L. An overview of long-term HM measurements around HADES URF. *Proceedings of the international symposium on multiphysics coupling and long term behaviour in rock mechanics*, Liège (2006) 15–26.
[3] Horseman S.T., Winter M.G. and Entwistle D.C. *Geotechnical characterization of Boom clay in relation to the disposal of radioactive waste*, Commission of the European Communities, EUR 10987 (1987).
[4] Baldi G., Hueckel T., Peano A. and Pellegrini R. *Developments in modelling of thermo-hydro-geomechanical behaviour of Boom Clay and clay-based buffer materials*, ISMES, Final report, EUR 13365/1 (1991).
[5] Mair, R. J., Taylor, R. N. and Clarke, B. G. *Repository tunnel construction in deep clay formations*. Final report, EUR 13964. Luxembourg: Commission of the European Communities (1992).

[6] Djéran-Maigre, I., Bazargan, B., Giraud, A. and Rousset, G. *Étude expérimentale du comportement thermo-hydro-mécanique de l'argile de Boom*. Rapport No. 94-002. Mol: SCK.CEN (1994).
[7] Lima, A. *Thermo-hydro-mechanical behaviour of natural Boom clay: an experimental study*. PhD thesis, Universitat Politècnica de Catalunya, Spain (2012).